BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 10070

SUBJECT: Evaluation of SPS Weather Avoidance Delta-V Requirements
Case 310

DATE: October 30, 1970

FROM: K. P. Klaasen

[redacted]

[redacted]

ABSTRACT

A mission independent allocation of 500 fps of SPS delta-V for weather avoidance (the currently budgeted amount) provides the proper splashdown point maneuverability required to avoid any adverse weather in the recovery area and to facilitate landing and recovery operations. This 500 fps includes (1) about 270 fps for movement of the splashdown point up to 500 n.mi. east or west at a time 24 hours before reentry for real-time weather avoidance and (2) about 230 fps for possible placement of the pre-mission nominal splashdown point somewhere other than the propellant optimum point because of landing and recovery considerations.

This mission independent allocation of 500 fps could be reduced to about 335 fps if two current ground rules were changed. If the real-time weather avoidance requirement of 500 n.mi. of translational capability east or west were changed to a requirement for a total of 1000 n.mi. of translational capability east plus west, only about 210 fps would be needed to satisfy the requirement since delta-V costs are greater for movements east than for movements west. If the constraint of 40° on the magnitude of the transearth return inclination were relaxed to around 60° for weather avoidance, the maximum delta-V requirement for placement of the nominal splashdown point somewhere other than the propellant optimum point would be halved.

The mission specific weather avoidance delta-V requirement may be as low as 100 fps in some cases. For a given mission, the real-time weather avoidance requirement of 500 n.mi. of translational capability could be reduced to about 200 n.mi. in those cases in which hurricanes are not a threat in the scheduled splashdown area. In addition, the date of the mission, the propellant optimum transearth return inclination, and the propellant optimum splashdown point determine whether or not the nominal splashdown point should be located somewhere other than the propellant optimum point and also determine the delta-V cost of moving the splashdown point. If it were possible to determine these mission specific weather avoidance requirements early enough to be included in the mission planning, additional SPS delta-V could often be made available for other uses.

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MEMORANDUM FOR FILE

Introduction

In order to increase the probability of successfully completing an Apollo mission, the spacecraft splashdown point upon return to earth must be chosen with care. The major consideration in choosing the splashdown point should be to facilitate a safe and rapid recovery of the crew and spacecraft. Such a recovery can be best accomplished in an area of the world which is free of large land masses, has generally favorable weather patterns throughout the year, and is reasonably accessible to our recovery fleets. For these reasons, an area in the Pacific bounded by 150°W and 170°W longitude and ±35° latitude has been chosen as the Apollo landing zone.

Minimization of the delta-V required for the transearth injection (TEI) burn (subject to several constraints) will determine a unique splashdown point within this acceptable landing zone that is optimum as far as SPS propellant usage is concerned. However, even within the acceptable landing zone, some splashdown points are more acceptable for landing and recovery than others, and it may be desirable to move the nominal splashdown point away from the point of minimum delta-V in order to improve landing and recovery conditions.

Maintenance of some capability to move the splashdown point in real time if bad weather should arise in the prime recovery area during the mission is also highly desirable. Significant range changes can be made during reentry by using aerodynamic lift (from a minimum range of 1200 n.mi. to a maximum range of 2500 n.mi. from entry interface at 400,000 feet altitude to the splashdown point). Use of the nominal reentry range (about 1350 n.mi.) is much preferred, however, since it reduces the probability of the spacecraft skipping out of the atmosphere and also minimizes crew recovery time. Therefore, weather avoidance using aerodynamic lift during reentry is not a desirable procedure and should be used only if required by off-nominal circumstances. Real-time weather avoidance can only be accomplished, then, by means of SPS maneuvers either at TEI or during the transearth coast.

In the current SPS delta-V budget that is used for mission planning, a mission independent allocation of 500 fps is made under the heading of weather avoidance. This 500 fps delta-V requirement provides for two things: (1) possible placement of the nominal splashdown point somewhere other than the point of minimum SPS propellant usage because of landing and recovery considerations and (2) the capability to move the splashdown point 500 n.mi. east or west at a time 24 hours before entry interface. Thus, any movement of the splashdown point away from the point of minimum SPS delta-V must be accomplished using the propellant provided in the 500 fps allocated to weather avoidance in the delta-V budget. Since at this time several proposed missions are made marginal or infeasible because of insufficient SPS propellant, it is appropriate that the requirements for weather avoidance be reevaluated.

Placement of Nominal Splashdown Point Away from Point of Minimum SPS Propellant Usage

Minimization of the SPS propellant required for TEI is accomplished by selecting a transearth trajectory for which the return inclination, return time, and splashdown point have been optimized subject to several constraints including the requirement that splashdown occur within the Pacific landing zone. It may be desirable to move the splashdown point in order to avoid land masses, improve recovery fleet deployment characteristics, or avoid any highly predictable, annual weather patterns. Delta-V must be allocated in the budget for this purpose because for the majority of mission planning, SPS propellant requirements are calculated using the propellant optimum splashdown point, and the changes in splashdown location required for landing and recovery are not included until late in the planning phase.

Of the factors which may lead to movement of the splashdown point away from the propellant optimum point, avoidance of annual weather patterns could potentially result in moving the splashdown point the greatest distance. Within the Pacific landing zone, the major predictable weather pattern is the Intertropical Convergence Zone (ITCZ), also known as the doldrums. The ITCZ is a narrow belt of low pressure stretching east and west and located near the equator. The very constant trade winds meet at this belt of low pressure, the trades being northeasterly in the Northern Hemisphere and southeasterly in the Southern Hemisphere. The ITCZ is characterized by hot, windless days with frequent showers and thundershowers. The width and location of this belt vary with the time of the year. In the Apollo landing zone, the ITCZ generally lies slightly north of the equator at about 3° to 5°N during the winter months with a width of about 2° and moves to about 7° to 10°N during the summer while expanding to about 4° in width. Because of the suddenness and frequency of rainstorms in this region, the ITCZ is undesirable for an Apollo recovery, and the nominal splashdown point will be placed outside of this zone if possible.

Since the ITCZ runs east and west, avoidance of this zone requires movement of the splashdown point north or south. Delta-V costs at TEI for movement of the splashdown point north or south are presented in Figure 1 for two typical missions.[1] The latitude of the splashdown point is largely determined by the earth-moon declination, and relatively large changes in return inclination are required to change the splashdown latitude only a few degrees. The cost of moving the splashdown point 1° (60 n.mi.) north or south is roughly 60 fps in delta-V at TEI.

Delta-V costs at TEI for moving the splashdown point east or west are generally quite low. East-west movement is accomplished simply by decreasing or increasing the transearth time of flight and letting the rotation of the earth move the splashdown point. Figure 2 shows that for flight times near that of minimum TEI delta-V, east-west movement across the entire Apollo landing zone costs less than 50 fps.[2]

In moving the splashdown point away from the point of minimum SPS delta-V for weather avoidance or other landing and recovery considerations, both the distance and direction of movement are very much mission dependent. In some cases, the point of minimum SPS delta-V may be perfectly acceptable for landing and recovery. In other cases, rather large changes are required. The actual delta-V requirement for a given mission can be determined if the date of the mission, the propellant optimum return inclination, and the propellant optimum splashdown point are known.

Delta-V costs at TEI could range from 0 fps to possibly as much as 250 fps. The 250 fps provides for north-south movement of the splashdown point across the entire width of the ITCZ at its maximum dimension of 4°. The capability to traverse the entire width of the band is required because at present there is an upper limit of 40° placed on the magnitude of the transearth return inclination. Thus, in the worst case, the propellant optimum splashdown point falls near the edge of the ITCZ with a return inclination of ±40°. Since the magnitude of the return inclination can only be decreased, north-south movement of the splashdown point can take place in only one direction, and the movement has to cross the entire 4° width of the band.

If the constraint on return inclination were relaxed for weather avoidance (while maintaining the constraint in determining the propellant optimum splashdown point), north-south movement of the splashdown point could take place in either direction in all cases. Then the worst case would occur for a propellant optimum splashdown point located in the middle of the ITCZ band, and the maximum translation required would be a 2° north-south movement. In this case, the maximum delta-V required at TEI would be reduced by half to about 125 fps. For the missions shown in Figure 1, the return inclination limit would have to be increased to about 60° for a 60-hour return time and to about 50° for an 83-hour return time to provide 2° of north-south movement.

Real-Time Weather Avoidance

SPS propellant must also be reserved to allow for avoidance of any adverse weather conditions that may exist in the prime recovery area at the time of splashdown. The weather under consideration here is short range, non-predictable weather rather than predictable, annual weather patterns. Within the Pacific landing zone, three main types of non-predictable weather occur that could force the movement of the splashdown point: (1) thunderstorms, (2) squalls, and (3) hurricanes or tropical cyclones. With the exception of these storms, winds are light to moderate (close to 0 knots in the doldrums, 10 to 15 knots in the trades) in the Pacific landing zone. Wave height is less than 6 feet. Fog occurs an average of only about once per year at any point within this zone.

Thunderstorms in the Pacific zone are nearly always thermal convective (due to localized surface heating) or orographic (due to topographical irregularities such as islands or mountains). Therefore, they are generally quite localized storms averaging 5 to 25 miles in diameter and never exceeding 200 miles in their greatest dimension. Such storms can form rapidly, often in as little as several hours. Since thunderstorms in this area are not usually associated with warm or cold fronts, their movements are quite restricted.

Squalls are lines of rain and high winds possibly several hundred miles long. They generally approach from the west or northwest and travel at about 30 knots. Squalls are short-term storms and usually last only 6 to 12 hours but may last up to 36 hours. Their behavior is often irregular and unpredictable.

Hurricanes are less frequent but much more massive and violent storms. They are circular and range in size from 50 to 600 miles in diameter. Hurricanes originate near the equator and initially move westward and slightly poleward at about 10 to 20 knots. As it reaches higher latitudes, the average storm will hook more and more poleward and may even loop back to the east at around 30° latitude. Individual storms, however, are sometimes erratic in their movements. Hurricanes may form in as little as 12 hours although they usually take several days to form. Within the Pacific landing zone, hurricanes have been reported only in the Southern Hemisphere and only during the months of November through April. The frequency of hurricane occurrence is somewhat uncertain. Data collected over the years by conventional means indicate that an average of between 2 and 3 hurricanes per year occur in the southern Pacific landing zone. However, recent weather satellite data indicate that conventional means may detect only about 1 out of every 4 hurricanes that actually form in remote ocean areas.

Based on the size and rate of movement of storms in the Apollo landing zone, it appears that the capability to change the splashdown point by 500 n.mi. as provided in the current budget would provide the proper maneuverability required to avoid any major weather system that might arise in the prime recovery area. In terms of SPS propellant, the least costly method of changing the splashdown point is to move it east or west by decreasing or increasing the return time. Thus, reserving sufficient SPS propellant to move the splashdown point by 500 n.mi. east or west either at TEI or sometime during the transearth coast will provide sufficient maneuverability for real-time weather avoidance.

There are three major constraints which determine the point in the mission timeline at which splashdown point changes can be made for the purpose of weather avoidance. First, the mission flight controllers are opposed to making any midcourse corrections for weather avoidance later than 24 hours before entry interface. Second, although delta-V costs for splashdown point translation are less the earlier the course correction is made, weather predictions made more than 24 hours in advance are not sufficiently reliable. Third, the recovery fleet can travel at a maximum speed of only about 20 knots. Therefore, a splashdown point change of 500 n.mi. would require at least 24 hours advance notice so that the fleet could reach the new splashdown point in time. For these reasons, any weather avoidance maneuvers must be performed at a time approximately 24 hours before entry interface.

Delta-V costs for a 500 n.mi. splashdown point change at 24 hours before reentry are shown in Figure 3 for two trans-earth return times.[1] The costs are nearly independent of return time and return inclination. The delta-V required to move the splashdown 500 n.mi. east (speed up the return) is greater than that required to move 500 n.mi. west and is about 270 fps for all missions. However, since delta-V costs are not equal for east and west movements of equal distance, requiring that the delta-V capability be available to move equal distances in both directions make inefficient use of available propellant. The same real-time weather avoidance capability provided by a 500 n.mi. movement east or west (total of 1000 n.mi.) can be provided by any combination of east or west movement totalling 1000 n.mi. About 210 fps provides for the movement of splashdown by about 600 n.mi. west or 400 n.mi. east. Thus, if the translational capability required for real-time weather avoidance were allowed to be asymmetrical, the 210 fps would provide the same weather avoidance capability as the 270 fps required for the symmetrical 500 n.mi. movement.

One drawback involved in allowing asymmetrical weather avoidance capability is the 500 n.mi. limit on recovery fleet mobility in a 24-hour time period. This drawback could be partially removed by changes in fleet deployment or recovery procedures such as (1) stationing the fleet at the center of the 1000 n.mi. range for splashdown rather than at the nominal splashdown point and then moving the fleet to the actual splashdown point after the weather avoidance maneuver has been made (or the spacecraft maneuver could move splashdown to the point at which the fleet is located if weather is acceptable there), or (2) allowing the spacecraft to float in the Pacific for the added time it would take the fleet to reach the splashdown point if the weather avoidance maneuver were greater than 500 n.mi.

Conclusions

As a mission independent requirement for weather avoidance and other landing and recovery considerations, 500 fps of SPS delta-V is a reasonable figure. Of this 500 fps, about 270 fps is required to provide for movement of the splashdown point up to 500 n.mi. east or west at a time 24 hours before reentry for real-time weather avoidance. This 270 fps requirement is nearly mission independent. The remaining 230 fps is available for placing the nominal splashdown point somewhere other than the point of minimum SPS propellant usage in order to improve landing and recovery conditions. The delta-V actually required for this purpose depends on the date of the mission, the propellant optimum return inclination, and the propellant optimum splashdown point. The requirement can vary from 0 fps to possibly 250 fps.

The mission independent weather avoidance requirement could be reduced to about 335 fps if two current ground rules were changed. First, if the real-time weather avoidance requirement of 500 n.mi. of translational capability east or west were changed to a requirement for a total of 1000 n.mi. of translational capability east plus west, only about 210 fps would be needed to satisfy the requirement since this delta-V provides for splashdown translation of 600 n.mi. west or 400 n.mi. east. Second, if the 40° constraint on the magnitude of the transearth return inclination were relaxed for weather avoidance, the maximum delta-V required for placing the nominal splashdown point somewhere other than the propellant optimum point would be halved. The actual delta-V required for this purpose would then range from 0 fps to only about 125 fps.

If the weather avoidance delta-V requirement used in mission planning could be made mission dependent, additional SPS delta-V could possibly be made available for other maneuvers. There are two ways in which the weather avoidance requirements could be made mission dependent. First, if the delta-V actually required for placement of the nominal splashdown point away from the propellant optimum point could be determined early enough, that delta-V requirement could be used in mission planning leaving the balance of the present budget allocation available for other SPS maneuvers. Second, the real-time weather avoidance requirement of 500 n.mi. of translational capability could be reduced in those cases where hurricanes are not a threat in the nominal splashdown area. If splashdown is not scheduled to occur in the Southern Hemisphere between November and April (as is true for Apollo 15 in the summer of 1971 and for Apollo 17 in the summer of 1972 under the current schedule of missions), a translational capability of only about 200 n.mi. should be sufficient to avoid any storms that might arise. The weather avoidance delta-V requirement could then be reduced by approximately 150 fps. Thus, the mission specific weather avoidance delta-V requirement could be as low as about 100 fps in some cases.

K. P. Klaasen

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Attachment

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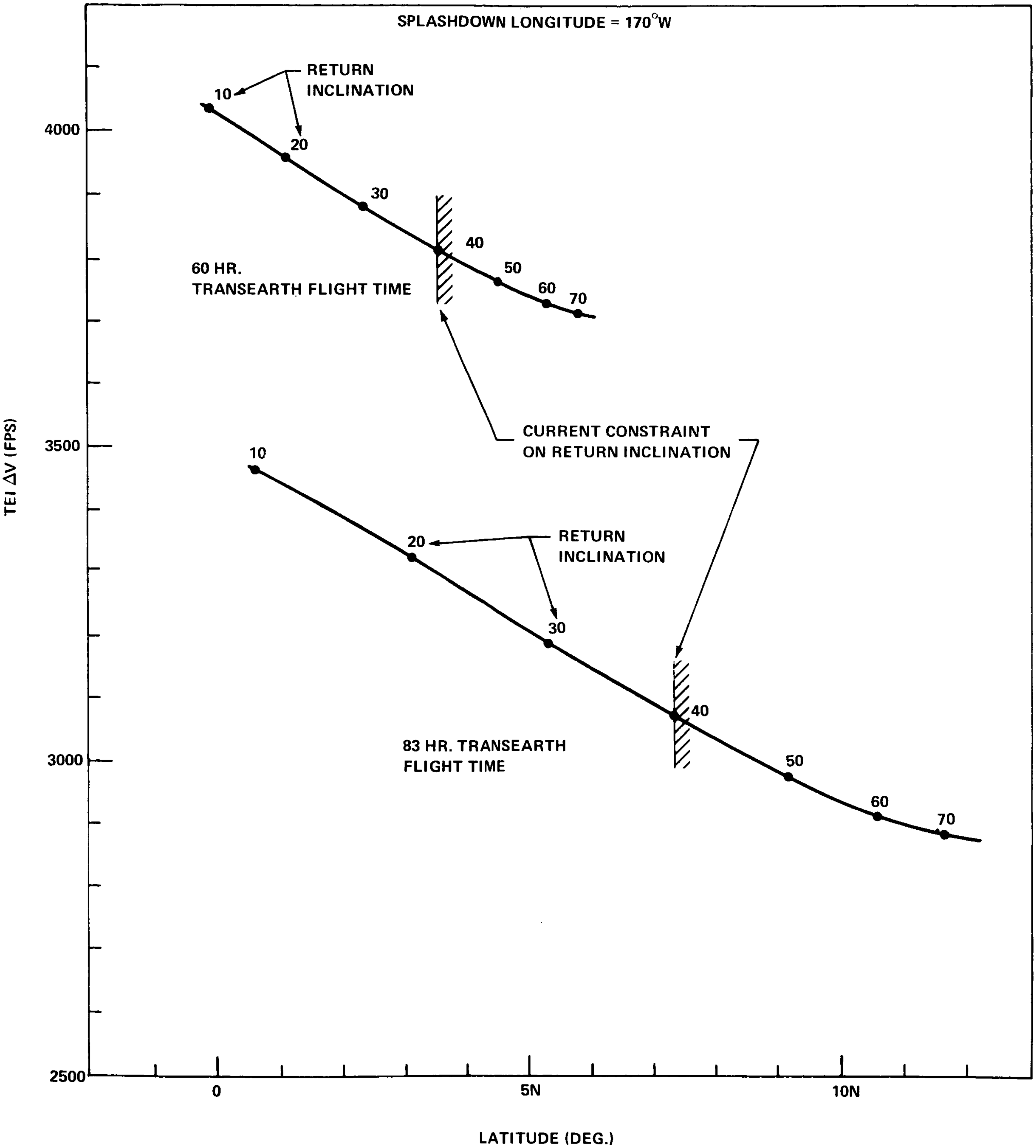

FIGURE 1 - TEI DELTA-V COSTS AS A FUNCTION OF SPLASHDOWN LATITUDE

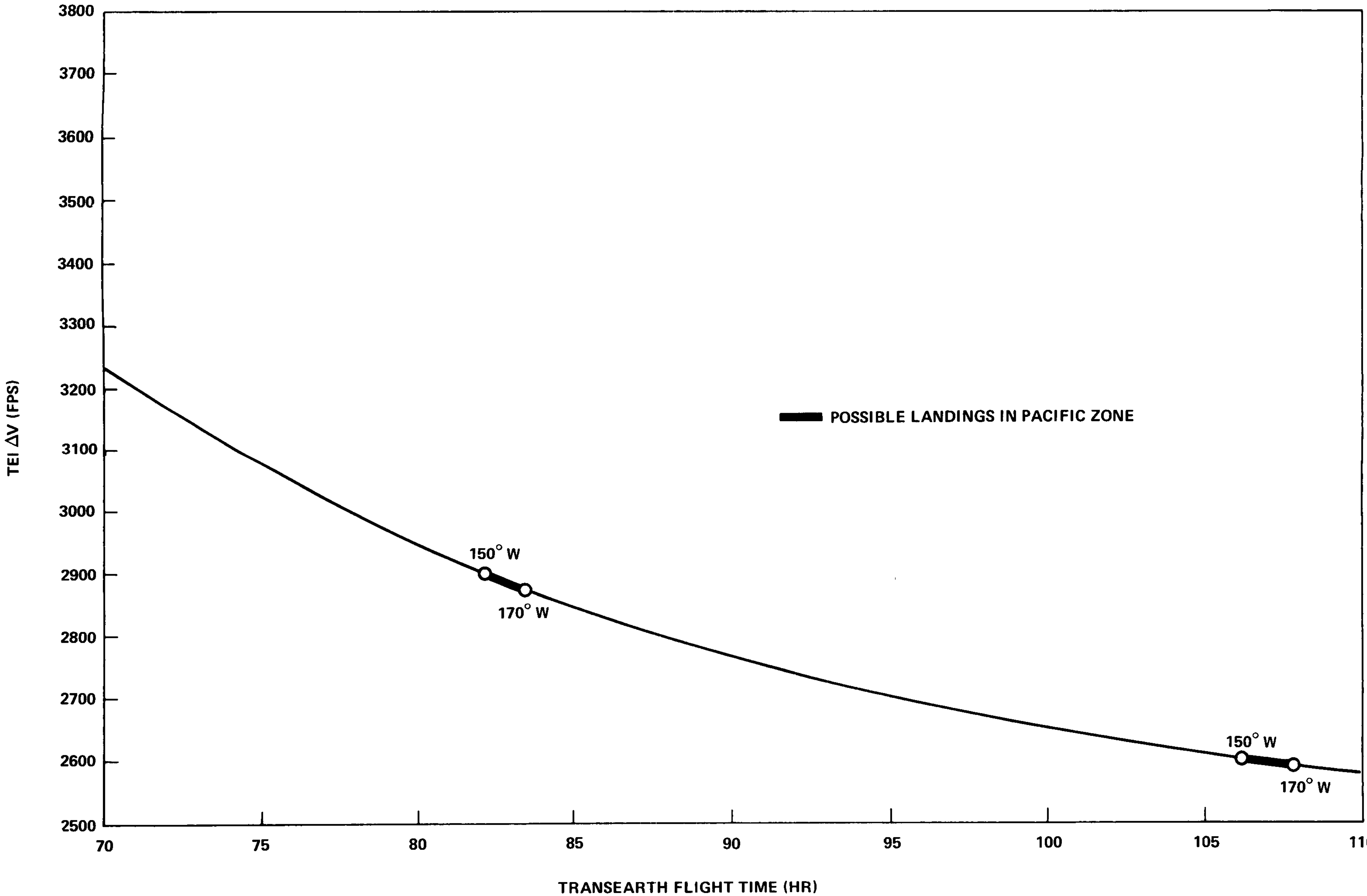

FIGURE 2 - TEI ΔV COST AS A FUNCTION OF TRANSEARTH FLIGHT TIME

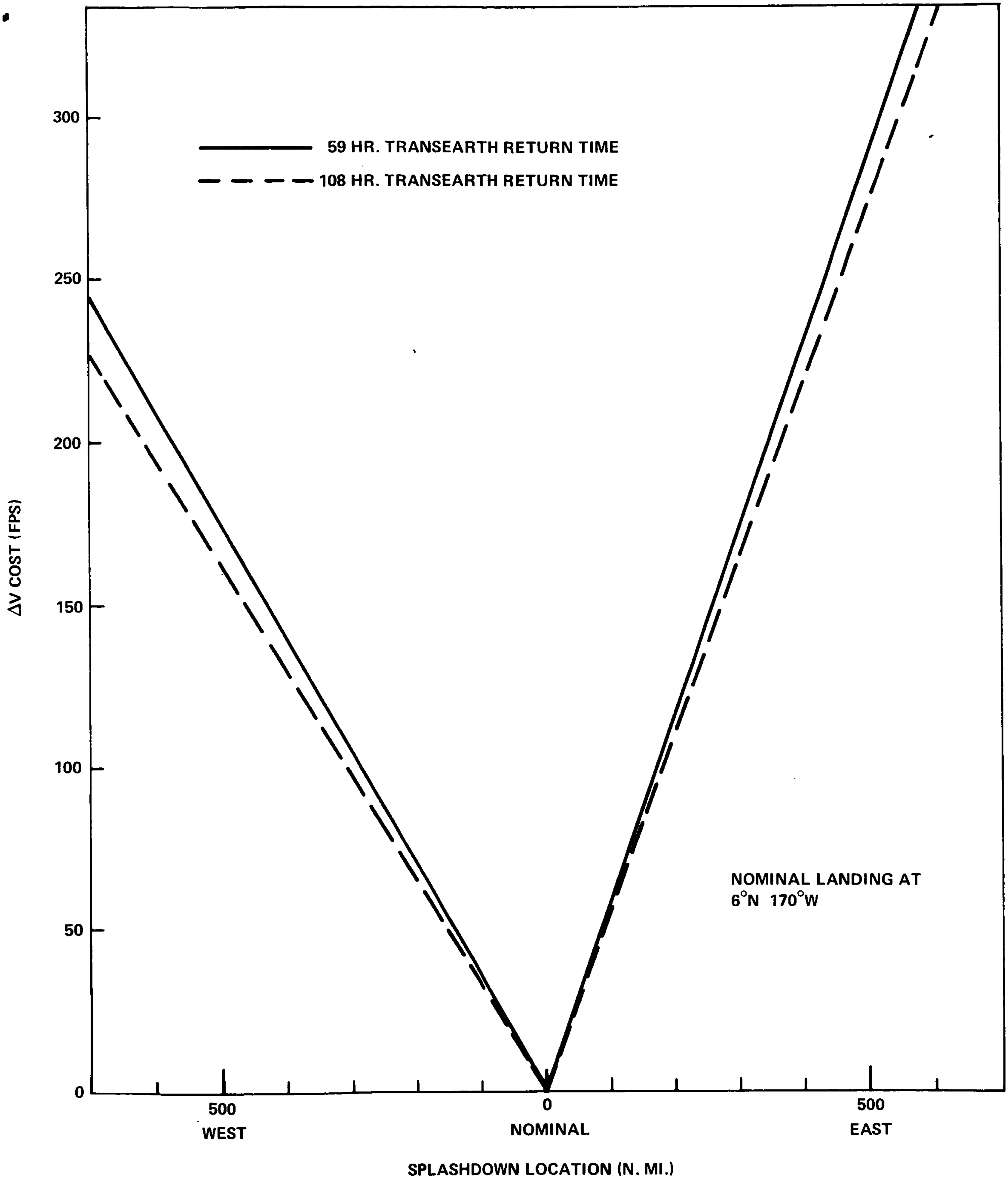

FIGURE 3 - DELTA-V COSTS FOR CHANGING SPLASHDOWN LONGITUDE AT 24 HOURS BEFORE REENTRY

BELLCOMM, INC.

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